Cialone, M.A., and Kraus, N.C. (2001). Engineering Study of Inlet Entrance Hydrodynamics: Grays Harbor, Washington, USA. *Proceedings of Coastal Dynamics 01*, ASCE, Reston, VA, 413-422.

ENGINEERING STUDY OF INLET ENTRANCE HYDRODYNAMICS: GRAYS HARBOR, WASHINGTON, USA

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Abstract: An extensive field data collection effort was undertaken in Fall 1999 to examine wave propagation and currents through an inlet entrance. These data support a circulation and wave model for Grays Harbor, Washington, a jettied entrance with a large tidal prism. Both the field data and model results show wave attenuation in the inlet entrance, flood currents strongest on the north side of the inlet, and ebb currents more uniformly distributed. The influence of the tidal current and water level on wave transformation was also examined. Ebb current produces the greatest change at the inlet entrance, increasing wave heights by as much as 0.5-1.5 m. Flood current increases wave height at the seaward end of the entrance due to the ebb shoal redirecting flow offshore, but reduces wave height in the inlet throat. Water level has a minimal impact on wave height in the inlet entrance, but does control wave height in the back bay.

INTRODUCTION

Grays Harbor is one of the largest inlets in the United States with a spring tidal prism of 5.5×10^8 m^3. Approximately 160 km^2 of 240 km^2 of bay area is emergent at low tide, indicative of expansive tidal flats. The entrance channel is approximately 9-12 m deep relative to mean lower low water, and the Federal navigation channel maintained on the south side of the inlet entrance is 12-13 m deep. As part of a U.S. Army Corps of Engineers (Corps) navigation study, data were collected at seven locations extending from seaward of Grays Harbor and through the entrance to record surface wave propagation and current through the inlet (Fig. 1). These measurements capture tidal flow and change of water level by tide and wind, as well as wave diffraction into the bay, processes that transport sediment into the navigation channel and over oyster-grounds leasing areas. Numerical models of waves and currents have been established for the entrance and bay at Grays Harbor as part of this study. This paper describes wave and current measurements

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2001**	2. REPORT TYPE	3. DATES COVERED **00-00-2001 to 00-00-2001**

4. TITLE AND SUBTITLE **Engineering Study of Inlet Entrance Hydrodynamics: Grays Harbor, Washington, USA**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Engineer Research and Development Center,Coastal and Hydraulics Laboratory,3909 Halls Ferry Road,Vicksburg,MS,39180-6199**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

Proceedings of Coastal Dynamics 01, Lund, Sweden, 11-15 June, 2001, ASCE, 413-422

14. ABSTRACT

An extensive field data collection effort was undertaken in Fall 1999 to examine wave propagation and currents through an inlet entrance. These data support a circulation and wave model for Grays Harbor, Washington, a jettied entrance with a large tidal prism. Both the field data and model results show wave attenuation in the inlet entrance, flood currents strongest on the north side of the inlet, and ebb currents more uniformly distributed. The influence of the tidal current and water level on wave transformation was also examined. Ebb current produces the greatest change at the inlet entrance, increasing wave heights by as much as 0.5-1.5 m. Flood current increases wave height at the seaward end of the entrance due to the ebb shoal redirecting flow offshore, but reduces wave height in the inlet throat. Water level has a minimal impact on wave height in the inlet entrance, but does control wave height in the back bay.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

and model simulations conducted to examine surface wave propagation through the inlet, including the modification of the waves by the tidal current and water level.

FIELD DATA COLLECTION

The data-collection program consisted of bathymetry surveys in the offshore and along maintained and natural channels; a LIDAR survey and controlled aerial photography of land and tidal flats during lower tide in the bay; measurement of water level at five locations around the bay periphery, wind and barometric pressureat a nearshore tower; and waves, water level, tidal current through the water column, and suspended sediment concentration at seven bottom-residing tripods. The tripod deployment interval of mid-September to mid-November 1999 spanned two lunar months (Hericks and Simpson 2000).

The tripods were deployed along or near the navigation channel (Fig. 1). Stations 1 through 6 extend from the entrance, through the inlet, and into the bay. Each tripod was configured with a SonTek Hydra, functioning as a directional wave gauge and an up-looking 1,500-kHz Acoustic-Doppler Profiler (Fig. 2). The Hydras contained a down-looking Acoustic-Doppler Velocimeter Ocean Probe, a high-resolution Resonant Pressure Transducer, and two optical backscatterence sensors. This instrument suite documented the waves, current near the bottom, and water level; the current through the water column in 0.5-m bins; and the suspended-sediment concentration through the inlet entrance. Station 0 (the seaward-most location) was configured with an Ocean Probe and an RDI Sentinel ADCP with directional wave-spectra firmware to determine if comparable data are derived from the two different measurement methods.

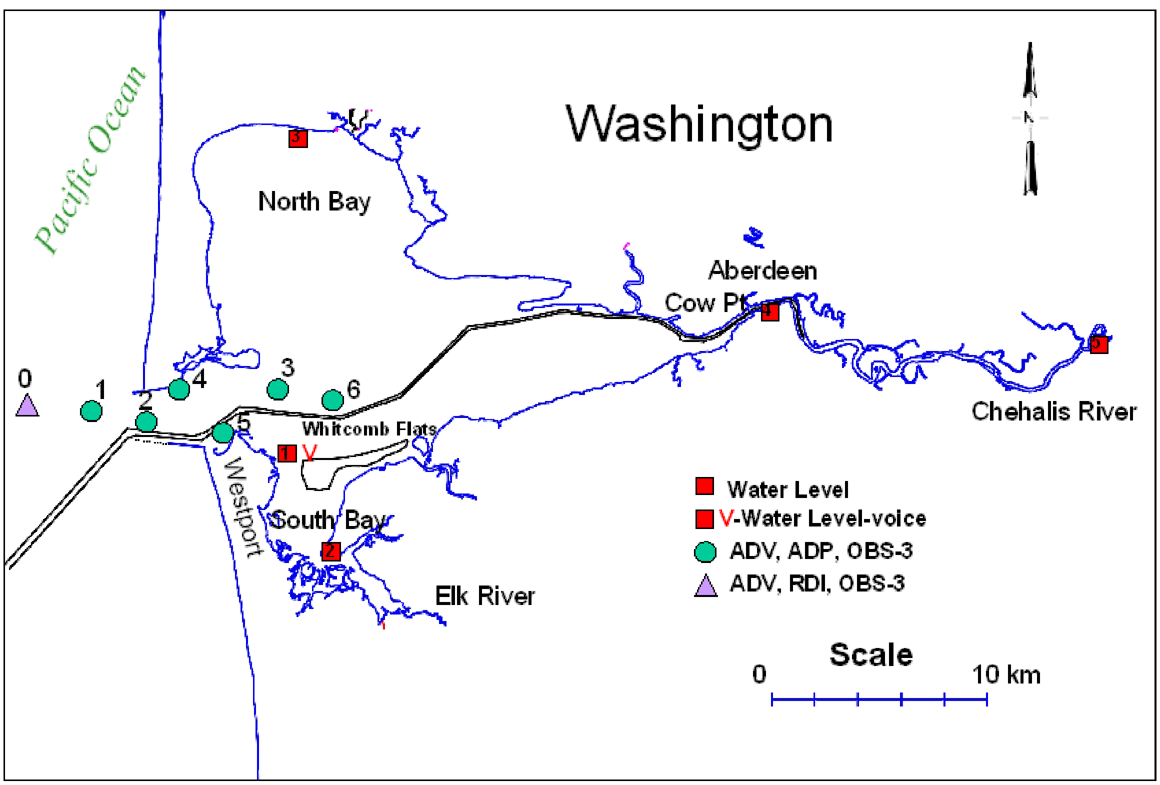

Fig. 1. Grays Harbor, Washington location map and field-data collection schematic

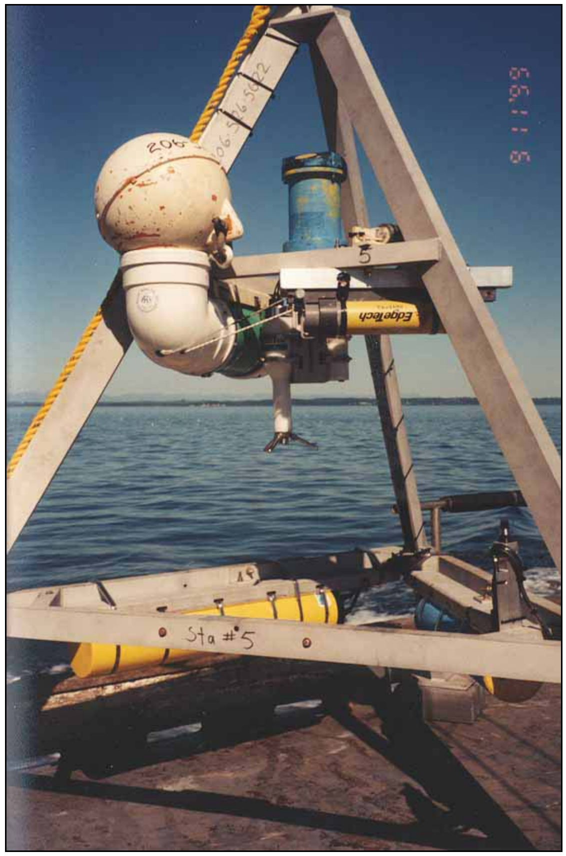

Fig 2. Instrument tripod

NUMERICAL SIMULATIONS

The field-data collection supports both circulation and wave numerical models for Grays Harbor. The ADvanced CIRCulation (ADCIRC) long-wave hydrodynamic model can define the circulation and water level associated with both tide and wind (Luettich et al. 1992). A two-dimensional (depth-averaged) version of ADCIRC was applied. The Corps' Coastal Inlets Research Program (CIRP) has enhanced ADCIRC to include flooding and drying, and it has exercised the model in shallow water estuarine conditions such as at Willapa Bay, Washington and as a reconnaissance-level study at Grays Harbor, Washington. The reconnaissance-level application of the ADCIRC model at Grays Harbor was enhanced and refined with field data collected in the Corps' navigation study.

The steady-state spectral wave model STWAVE has been modified in the CIRP to represent the wave-current interaction including the wave-action equation, current-induced breaking, and wave blocking by a current (Smith et al. 1999). Communication between ADCIRC and STWAVE is necessary in this study for computing wave-generated currents through the transfer of the radiation stresses from STWAVE to ADCIRC and the transfer of tide-, wind-, and wave-generated currents from ADCIRC to STWAVE. In addition to improved wave modeling in the presence of a strong current, STWAVE will give reliable estimates of sea-state in the channel. It can also quantify storm wave conditions as a function of the wind. The CIRP is presently upgrading STWAVE to include diffraction through a gap, as found at the Grays Harbor jetties that open to the bay.

Tidal Circulation Modeling

A finite-element grid was developed for the ADCIRC model to simulate water surface elevation and circulation as a function of tidal and wind forcing over the entire Grays Harbor region (Fig. 3). The ADCIRC grid contains 31,838 elements and 16,916 nodes, with the finest resolution along the federal navigation channel. The shoreline north of Grays Harbor (known as Ocean Shores) also shows fine grid resolution and is part of another coastal study. The ADCIRC model was driven with the Le Provost et al (1994) tidal constituent database for the field-data collection time period (September to November 1999). Figure 4 is a time-series of water surface elevation from the field data collection time period and computations at South Bay and Aberdeen (see Fig. 1 for locations). Model results correspond to the field data both in amplitude and phase at both the southern and eastern ends of the bay. Figure 5 is a time-series of current speed from the field data collection time period and computations at Inlet Stations 2 and 4. Computations correspond to the field data in amplitude with slight phase differences, attributable to bathymetric inaccuracies. Ebb and flood current data and model results show the strongest flood currents are on the north side of the inlet. Ebb currents are more uniformly distributed (Fig. 6).

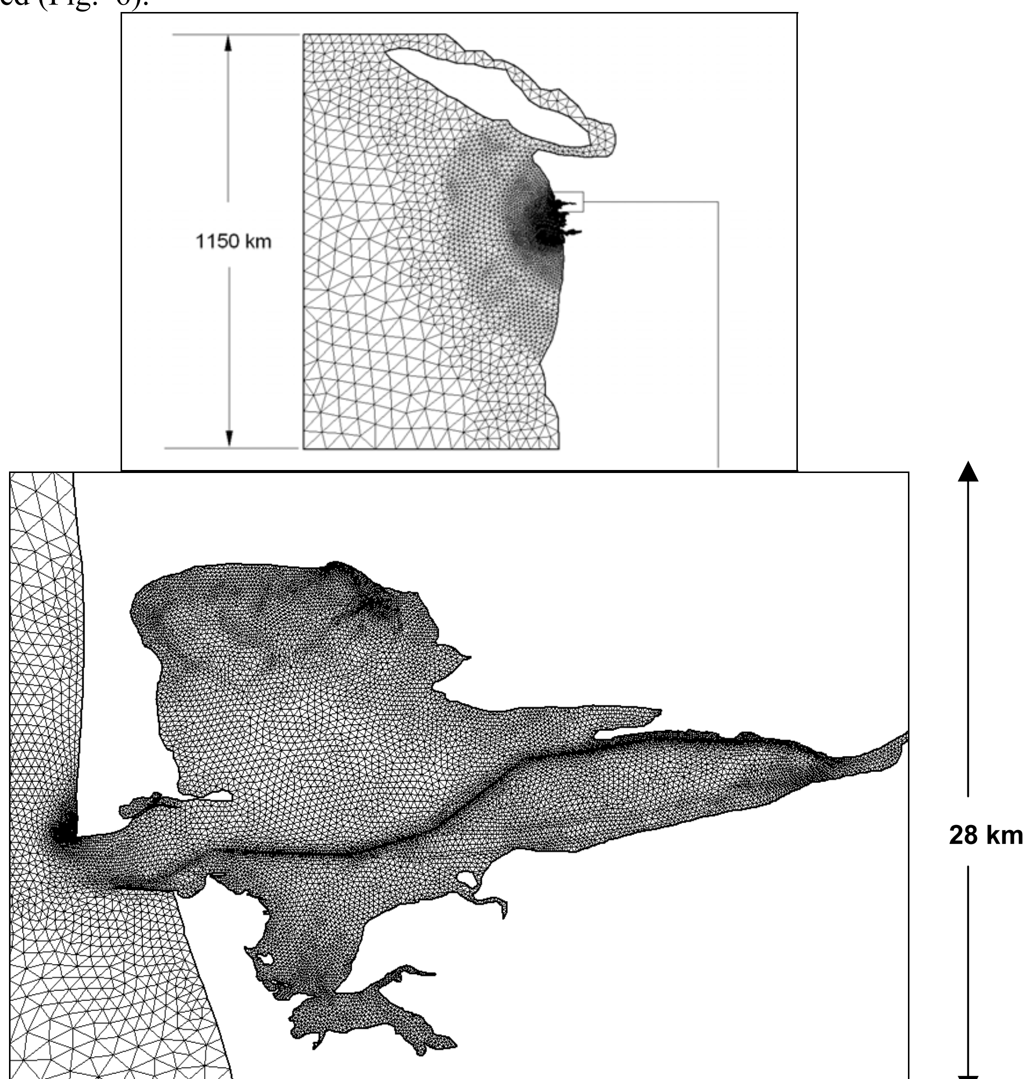

Fig 3. ADCIRC computation grid and details of Grays Harbor, Washington portion of the grid

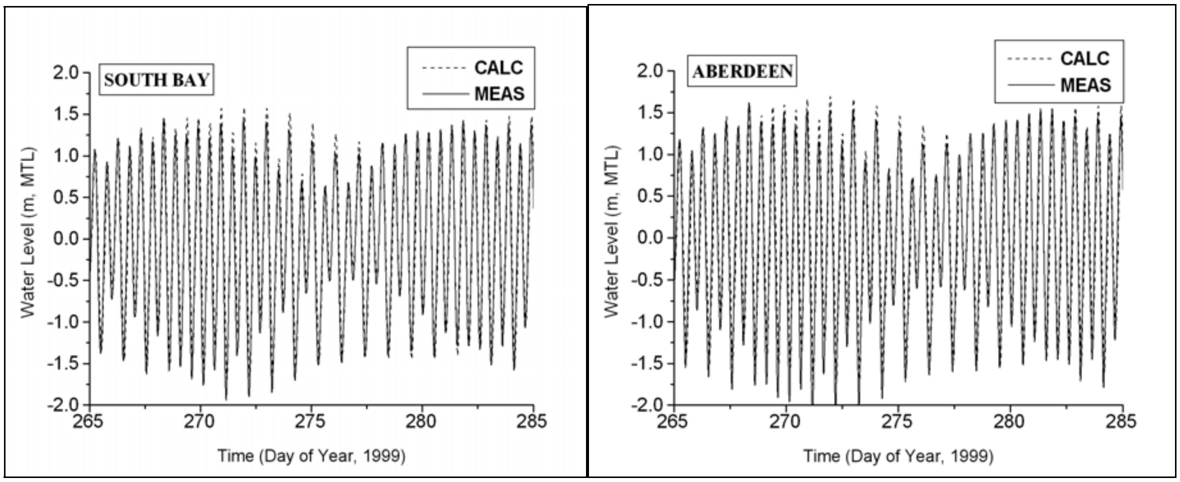

Fig 4. Comparison of measured water levels and ADCIRC model results at bay stations 2 and 4

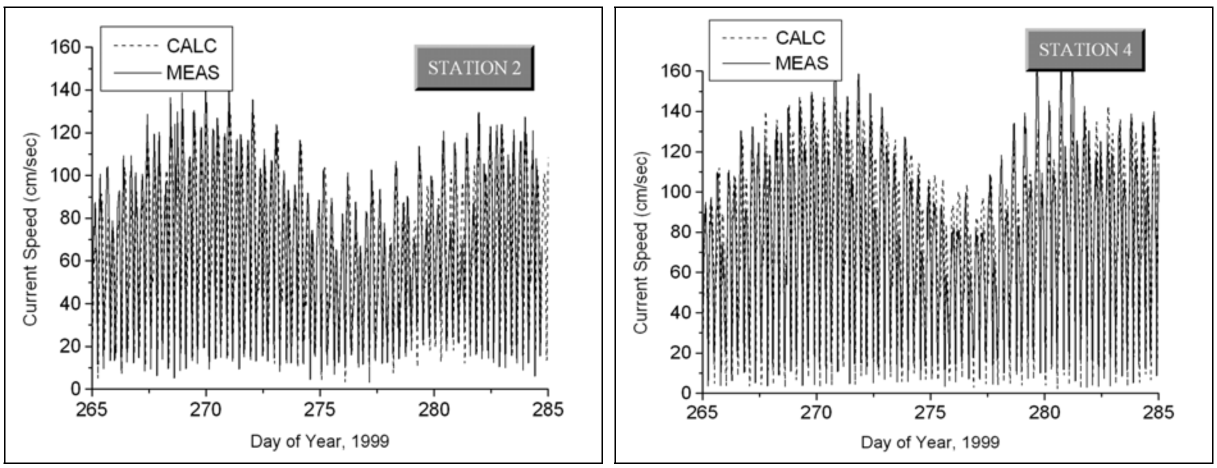

Fig 5. Comparison of measured currents and ADCIRC model results at inlet stations 2 and 4

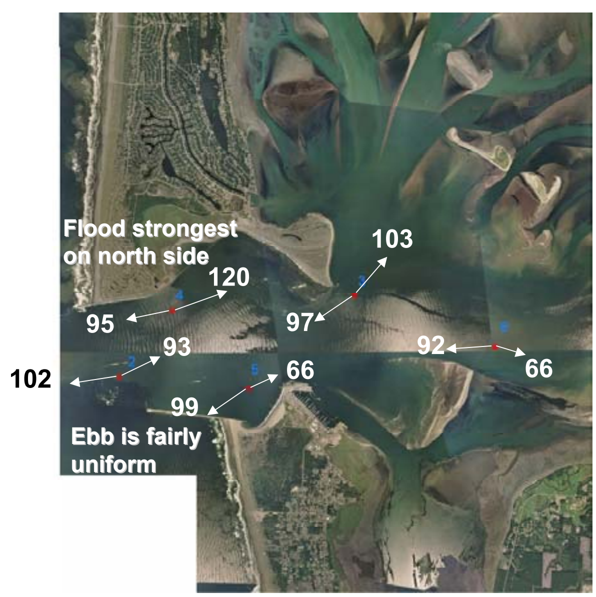

Fig 6. Average peak ebb and flood currents (cm/sec) for first month of field data collection

Wave Propagation Modeling

A computational grid for the region shown in Fig. 7 was developed for the spectral wave model STWAVE, which computes nearshore wind-wave growth and propagation (Resio 1987, 1988a, 1988b; Davis 1992). (This application did not consider wind-wave growth because the 9-km fetch had a limited effect on wave height (typically less than 15%).) Bathymetric data were obtained from the U.S. Army Engineer District, Seattle 1999 annual survey and from the GEOphysical DAta System GEODAS database of Hydrographic Survey Data (National Geophysical Data Center of NOAA). The vertical datum was adjusted from mean lower low water to mean tide level with the Westport (Fig. 1) tidal benchmark adjustment of 1.5 m. Tidal elevation data were added to the mean tide level bathymetry for each simulation where the influence of tide level was considered. The grid orientation is 10 deg west of north to align the longshore axis with the offshore bathymetric contours (Fig. 7). The STWAVE grid had 341 cells in the cross shore direction and 588 cells in the longshore direction with a cell size of 50 x 50 m.

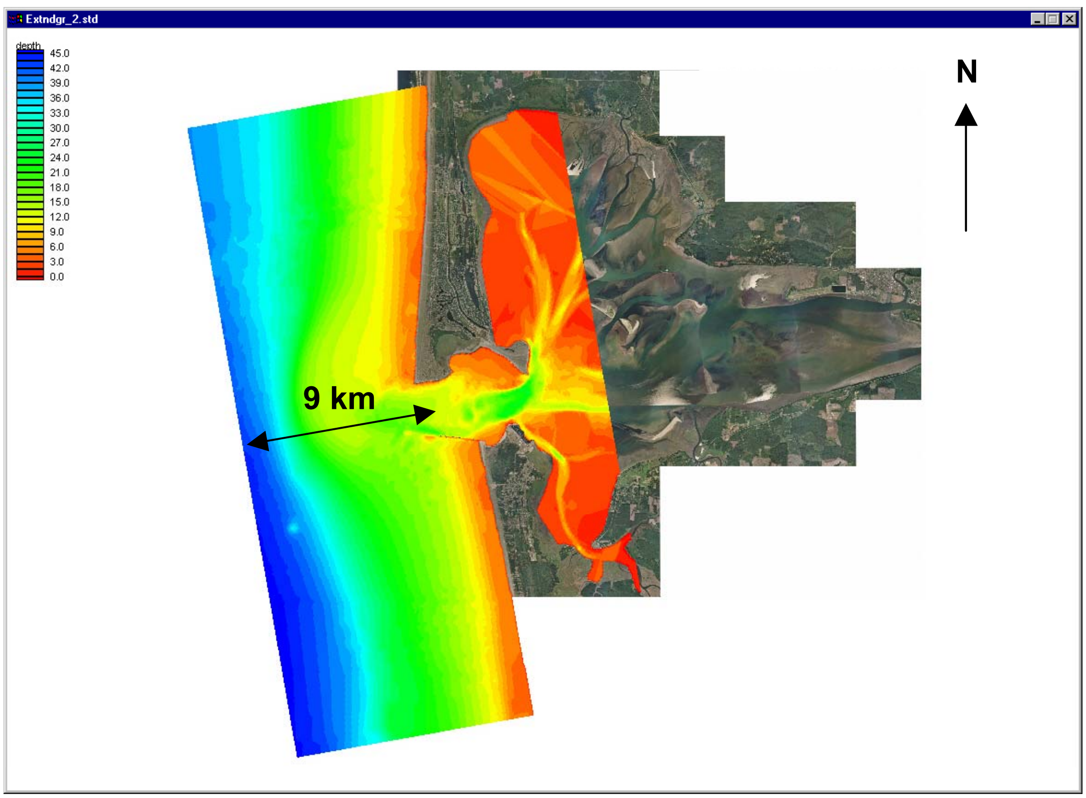

Fig 7. STWAVE model domain used in navigation study

STWAVE simulations of the first month (11 September –14 October) of the 2-month period of field data collection (11 September through 17 November 1999) were accomplished by driving the model with the Grays Harbor Coastal Data Information Program (CDIP) buoy wave spectra at 3-hr intervals. The CDIP buoy is located at 46^{o} 51.47' north latitude and 124^{o} 14.64' west longitude, approximately 9 km southwest of the entrance to Grays Harbor in a depth of 40-42 m. One-dimensional frequency spectra from the CDIP Datawell buoy at Grays Harbor (03601) were obtained from the CDIP web site. A theoretical directional spread was applied to the frequency spectra to create 2-D spectra

for input to the STWAVE model. The two-dimensional spectra were rotated 10-deg west of north to correspond with the grid orientation. Tide elevation data from Water Level Station 1 were used to modify depth for each 3–hr time period to account for water level (and depth) fluctuations of the tide.

Model validation with the field data shows good correlation. A preliminary comparison of wave height at seven wave gauge locations (Stations 0 through 6 in Fig. 1) to the model results at these locations is given in Fig. 8. Wave attenuation from Station 0, to Station 2, to Station 3, to Station 6 is clearly evident. The maximum wave height at Stations 0 through 2 is over 4 m. Wave heights at Stations 4 and 5 (in the inlet throat) do not exceed 2.8 m during this same time period. Wave height at Station 3 does not exceed 1.2 m and at Station 6 (most bayward) does not exceed 0.4 m. All stations show some evidence of tidal influence, with the most predominant influence at the interior stations (Stations 3 and 6). The difference between measured and calculated wave height shows that model results are typically within 0.5 m of the measurements.

Impacts of Currents and Water Level on Wave Transformation

Climatological conditions were determined from the CDIP buoy data (August 1993 through November 1999). The wave climate was divided into 6 height, 5 period, and 6 significant angle bands to drive the STWAVE model, for a total of 180 STWAVE simulations (Table 1). Wave conditions were first run at mean tide level (MTL) with no current. These base condition results were monitored at all inlet data-collection locations (Fig. 1). The majority (45.1%) of the waves are in the1-2 m range and result in waves at the entrance to Grays Harbor of approximately 0.5 to 2 m. Wave heights in the 2-3 m range at the CDIP buoy have a 24.7% occurrence, producing waves of 0.5-3 m at Grays Harbor entrance. The largest waves (>6.5 m) have a probability of occurrence of less than 1%, but result in wave heights of 1-8 m in the inlet entrance. Wave heights at Tripod Station 3 (bayward side of the inlet entrance) have an 80% probability of being less than 1 m.

Table 1. Wave Conditions from Grays Harbor Wave Climate (1993-1999)

Significant Wave Height, m	Peak Period, sec	Wave Direction, Deg from North	Compass Direction
0.5	6	202.5	SSW
1.5	8	225.0	SW
2.5	12	247.5	WSW
3.5	16	270.0	W
5.0	20	292.5	WNW
6.5		315.0	NW

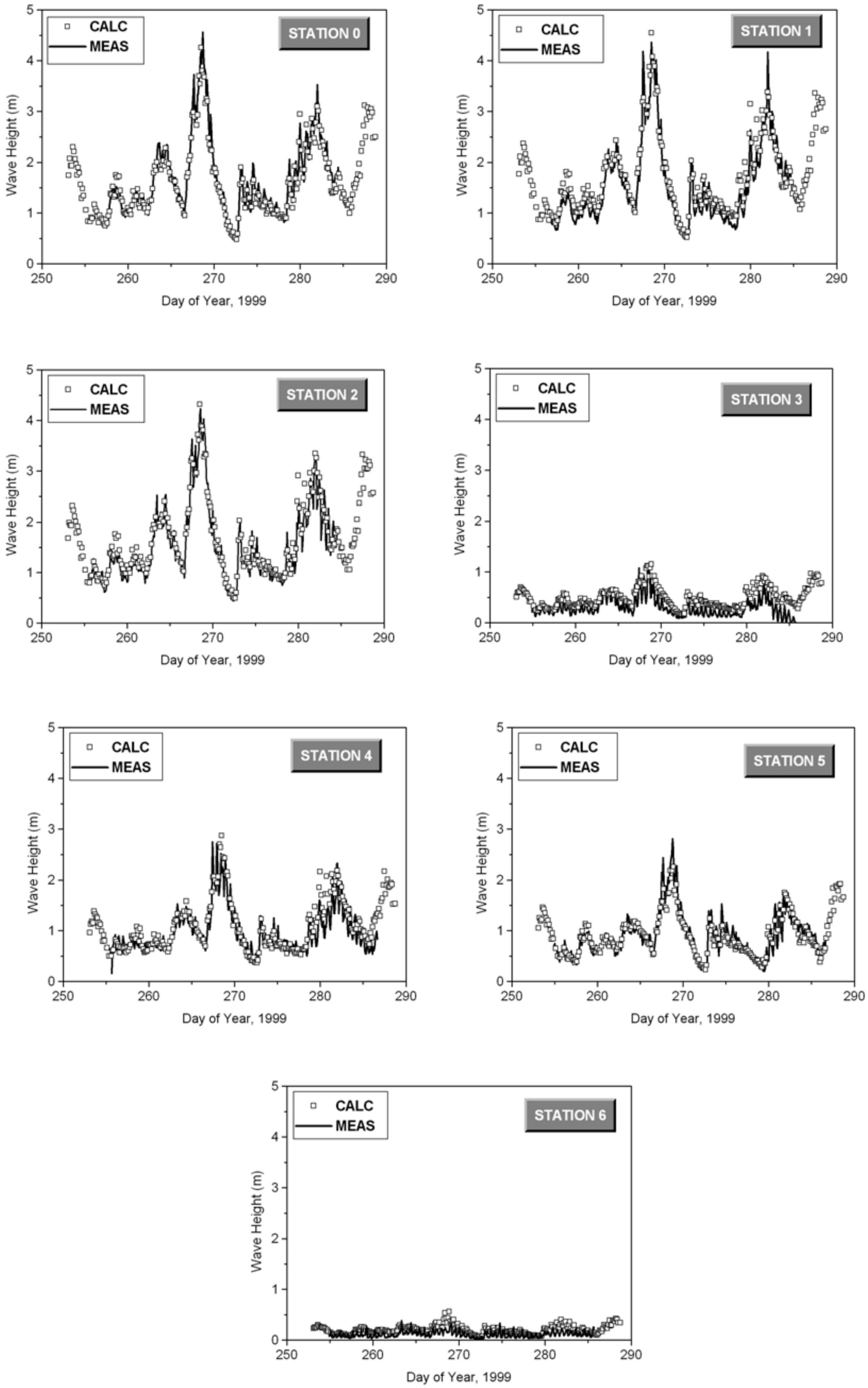

Fig 8. Comparison of measurements of wave height and STWAVE model calculations

The climatology simulations were then made at different tide stages and currents. Conditions were selected based on analysis of data, which showed that slack currents in the inlet occur near the time of mean high water and mean low water and maximum currents occur near the time of MTL. Ebb and flood currents were obtained from an ADCIRC simulation and interpolated onto the STWAVE grid. "Peak" currents, on the order of 0.8-0.9 m/sec, were selected for a typical mean tide cycle and do not represent maximum conditions that can occur at Grays Harbor. (The maximum current at the entrance during the first deployment period was 1.7 m/sec.) The tide range was approximately 2.1-2.2 m, which is equivalent to the mean tide range, whereas the spring tide range is on the order of 3 m. These simulations demonstrate the influence of water level and current on waves in the Grays Harbor entrance. Figures 9 and 10 show differences in wave height at Station 2 for the various currents and water levels versus wave heights with no current or water level variation. Water level has minimal influence on wave height in the inlet entrance under most conditions. Flood currents increase wave height at Station 1 (due to the ebb shoal bathymetry redirecting flow offshore), but reduce wave height at Stations 2 and 3. Ebb currents cause a significant increase in wave height at all stations for most wave conditions.

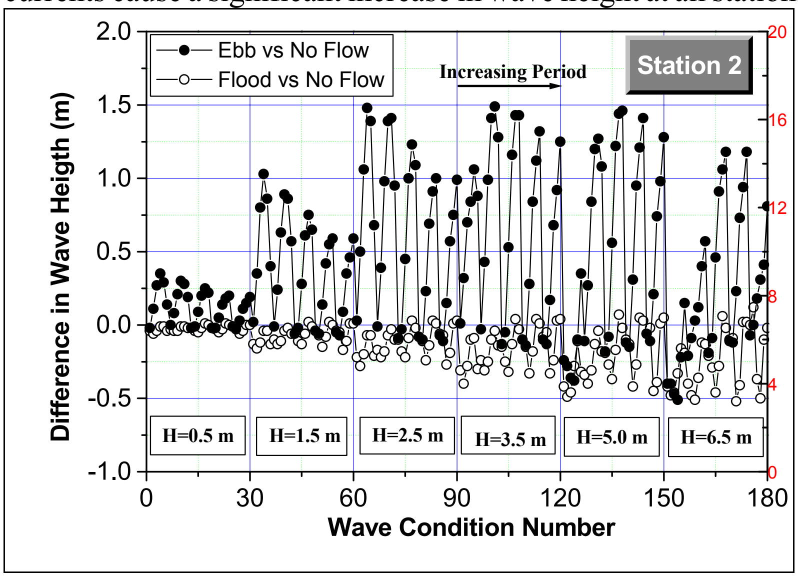

Fig 9. Influence of current on wave height

(Each group of 30 wave conditions reflects 5 wave periods and 6 wave directions)

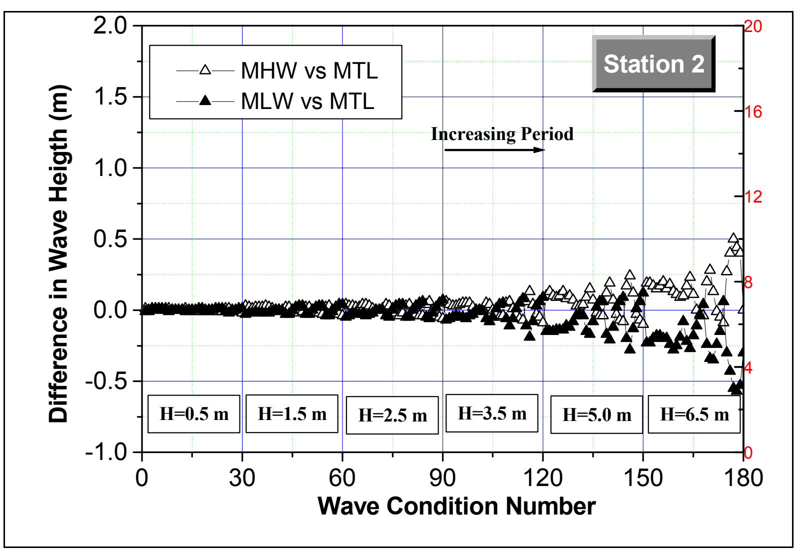

Fig 10. Influence of water level on wave height

(Each group of 30 wave conditions reflects 5 wave periods and 6 wave directions)

CONCLUSIONS

An extensive hydrodynamic study of Grays Harbor, Washington was conducted including data collection in Fall 1999and numerical model simulations. The measurements show considerable wave attenuation through the inlet throat (factor of 10 decrease), flood currents strongest on the north side of the inlet, and ebb currents more uniformly distributed. The numerical models include wave and tidal circulation simulations and the effects of tidal currents and change in water level on waves in an inlet entrance. Ebb currents have the greatest influence and increase wave height 0.5-1.5 m. Flood currents increase wave height at the seaward end of the entrance due to a local bathymetry-induced flow reversal and reduce wave height (flatten waves) further inside the inlet entrance. Water level has a minimal impact on waves in the inlet entrance, but does control wave transformation in the back bay. Examination of the effect of tidal currents on wave transformation and the modification of the current through wave radiation stresses will be examined in the next stage of dynamic linking of models through the CIRP Steering Module.

ACKNOWLEDGEMENTS

This work was performed as part of a mission-support activity for the U.S. Army Engineer District, Seattle. Permission was granted by Headquarters, USACE to publish this information. The cooperation of instrument manufacturers named in this work is acknowledged, but no endorsement of equipment is implied.

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